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ABSTRACT
Vast quantities of spent fuel are available for safeguard measurements, primarily in Commonwealth of Independent States (CIS) of the former Soviet Union. This spent fuel, much of which consists of long-cooling-time material, is going to become less unique in the world safeguards arena as reprocessing projects or permanent repositories continue to be delayed or postponed. The long cooling time of many of the spent fuel assemblies being prepared for intermediate term storage in the CIS countries promotes the possibility of increased accuracy in spent fuel assays. This improvement is made possible through the process of decay of the Curium isotopes and of fission products. An important point to consider for the future that could advance safeguards measurements for reverification and inspection would be to determine what safeguards requirements should be imposed upon this "new" class of spent fuel. Improvements in measurement capability will obviously affect the safeguards requirements. What most significantly enables this progress in spent fuel measurements is the improvement in computer processing power and software enhancements leading to user-friendly Graphical User Interfaces (GUI's). The software used for these projects significantly reduces the IAEA inspector's time expenditure for both learning and operating computer and data acquisition systems. At the same time, by standardizing the spent fuel measurements, it is possible to increase reproducibility and reliability of the measurement data. Hardware systems will be described which take advantage of the increased computer control available to enable more complex measurement scenarios. A specific example of this is the active regulation of a spent fuel neutron coincident counter's ^{3}He tubes' high voltage, and subsequent scaling of measurement results to maintain a calibration for direct assay of the plutonium content of Fast Breeder Reactor spent fuel. The plutonium content has been successfully determined for the fast breeder reactor assemblies with contact radiation levels as high as 10^5 Rads/hr. Using limited facility information and multiple measurements along the length of the assembly, the combined measurement and facility declaration error is ~8%. A simplified one-point measurement procedure and generalized analysis leads to a combined measurement and facility declaration error of ~13%.

INTRODUCTION
A large international safeguards program is presently underway to improve the safeguards and security of spent nuclear fuel from the BN-350 fast-breeder reactor in Aqtau, Kazakhstan. To satisfy International Atomic Energy Agency (IAEA) and Kazakhstan Atomic Energy Agency (KAEA) requirements, the plutonium content of these fuel assemblies must be measured before they are repackaged and relocated to difficult-to-access, long-term storage. The accurate nondestructive assay of the plutonium content of BN-350 spent fuel was feasible because the reactor physics and operation are such that even at the highest fuel burnup levels, the buildup of the curium isotopes remains very low. The spontaneous fission neutrons generated by the spent fuel are dominated by

^{238}Pu and ^{240}Pu. ^{242}Pu and the curium isotopes generate a negligible amount of the spontaneous fission neutrons.

Our measurement technique is to observe the singles and doubles (coincidence) neutron rates in a ring of ^{3}He proportional counters imbedded in polyethylene surrounding the given fuel assembly while underwater in the facility storage pond. The singles and doubles neutron rates are converted into the plutonium content of a given assembly. The analysis is based upon a determination of the relationship between the raw experimental neutron rates and the plutonium content of the BN-350 fuel assemblies. The main steps in determining these relationships were (1) the experimental determination of our neutron counter's response to various arrangements of fresh mixed oxide (MOX) fuel, (2) Monte-Carlo N-Particle [2] (MCNP) modeling of these fresh MOX fuel experiments, (3) MCNP modeling of various BN-350 assembly types, and (4) calculations of the relative amounts of various neutron-emitting isotopes in the BN-350 spent fuel. The facility used operator records and a computer code to make declarations of the plutonium content of the BN-350 spent-fuel assemblies. The conclusion of the packaging campaign was recently announced in a *Wall Street Journal* article on June 4, 2001, titled "U.S., Kazakhstan Talk of Plutonium Security."[1]

THE SPENT FUEL COINCIDENCE COUNTER

Our instrument, which the IAEA has named the Spent Fuel Coincidence Counter (SFCC), has the outward appearance of a right cylinder with a hole along the axis through which a fuel assembly can pass.[3] The other regions of the SFCC consist of a ring of 20 ^{3}He tubes and an ionization chamber imbedded within cylindrical pieces of polyethylene. To keep the gamma-ray dose rate low enough in the ^{3}He tubes for them to function properly, the inner regions of the instrument contains 6.8 cm of lead shielding. Cross sectional plan and side views of the SFCC are shown in Figs. 1 and 2. Each of the 20 ^{3}He tubes were connected to Precision Data Technology (PDT) 110A preamplifiers. Measurements and MCNP calculations of the die-away time, τ, with the SFCC underwater, vary from approximately 80 to 110 μs, depending on the fissile content of the fuel placed inside the counter. The optimum value of the shift register gate width is $G=1.27\times\tau$ [2]. Given the expected range of die-away times with the SFCC underwater, a fixed gate width of $G=128$ μs was chosen. The standard predelay of $\tau_{pre}=4.5$ μs is used. [4]

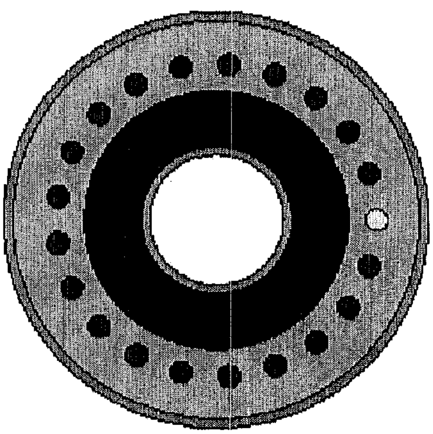

Fig. 1. Cross sectional plan view of the SFCC.

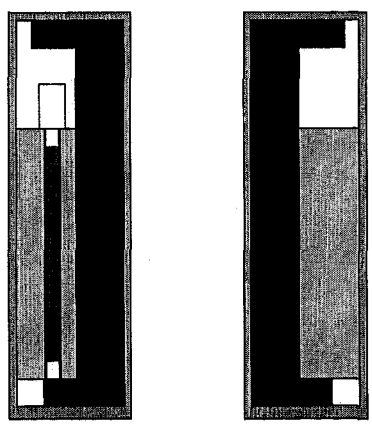

Fig. 2. Side plan view of the SFCC.

By studying the response of the ^3He tubes to high gamma-ray fluxes from 1 to 100 Rads/hour, it was concluded that at the operation voltage of 1600 V the ^3He tubes were insensitive to gamma rays at radiation levels at the tubes of less than 50 Rads/hour. The tube efficiency could be made closer to unity by an increase in the operating voltage but this would lead to an increased sensitivity to gamma rays. If the Ionization Chamber in the SFCC measured a dose rate of higher than 50Rads/hr, the software automatically adjusted the high voltage to a lower predetermined value and adjusted the count rates accordingly via scaling factors. This operation maintained a single calibration set for the determination of the plutonium mass for the spent fuel assemblies.

SFCC SOFTWARE FOR DATA ACQUISITION AND ANALYSIS

A simple Windows-based user interface was developed to enable routine spent fuel measurements with the SFCC by IAEA nonspecialists in the Republic of Kazakhstan. This software was accepted for routine use by the IAEA. The software communicates with the SFCC acquisition electronics and dynamically adjusts measurement and analysis parameters based upon both user inputs and the current measurement condition. The software is a shell program that sends control functions to other programs on the main computer or embedded within the acquisition electronics themselves. The prompts to the operator at each window for the SFCC program are given with a voice notification, in both English and Russian, at both the data acquisition control room and on the spent fuel pond floor. These audio indicators are provided in addition to standard visual indicators given via the computer screen. These prompts are given as such because the operating environment is loud and distracting, and the multiple notifications help maintain the work schedule and minimize confusion. The working language of the facility operator is Russian, while that of the IAEA inspector is typically English. This is complicated by the fact that the facility operator and IAEA inspector are located in into two different rooms separated by about 20 meters.

The opening computer program screen, shown in Fig. 3, initializes communications with the acquisition electronics analysis programs and provides a login screen for the inspector along with optional dialog boxes.

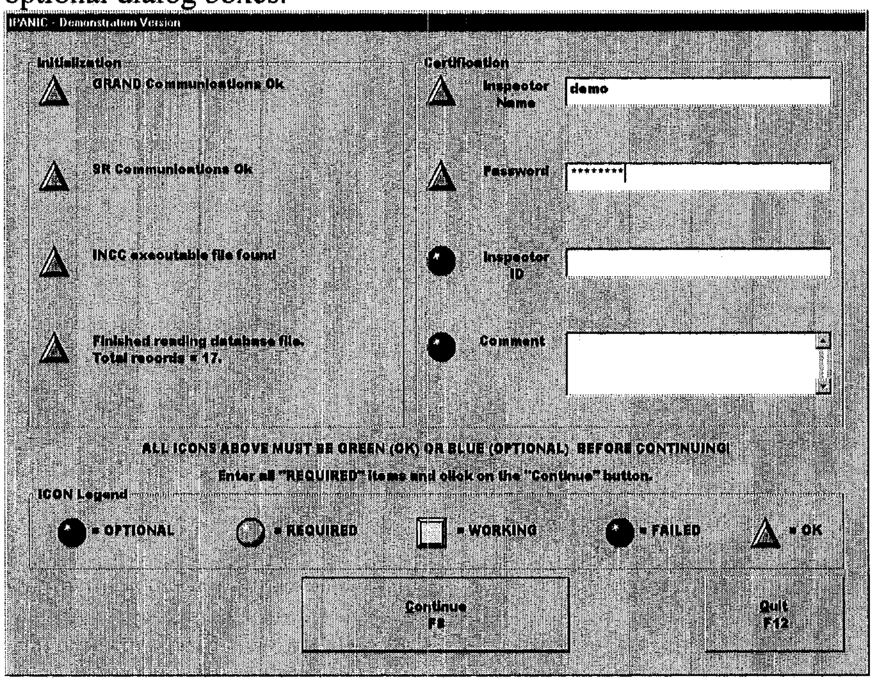

Fig. 3. Opening screen of the SFCC data acquisition and analysis program.

Specific information about the spent fuel assemblies to be measured with the SFCC is entered into a dialog box that appears as shown in Fig. 4. The following information was used to determine the analysis parameters used for the spent fuel characterization in the Kazakhstan project: declared total plutonium content–used to compare to measured plutonium content to determine if the specific assembly passes or fails IAEA criteria; assembly type–driver or Blanket for which generic isotopic relationships are used to complete the analysis. The "Other" option provides the capability for the software to direct the user to perform a series of measurements over an integral area using either blanket or driver generic isotopics; these results would then be summed together to complete an assay on disassembled items. A number of assemblies were assayed once they had been stabilized into Argon or water filled canisters; these options allow for slight corrections to be applied to the analysis to take into account these different measurement geometries. The scaling factor for individual pins was never used but was an option originally programmed into the software.

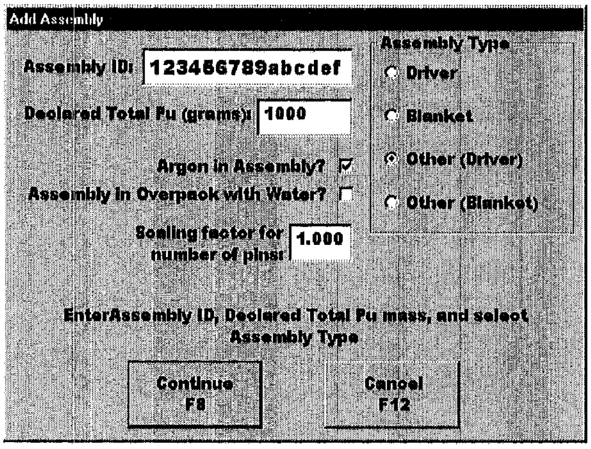

Fig. 4. Spent fuel assembly data entry window.

Some user interaction is also required during the measurement process, such as the entry of the spent fuel assembly ID, visible to the IAEA inspector via an underwater camera. The window to accomplish this task is shown in Fig. 5. Most of the windows within the program display current acquisition electronics status and measurement results in real time, in the sidebars to the right of the screens. Additional information displayed in these sidebars also indicates to the operator the Z-axis positioning of the crane used for spent fuel assembly movements and the Load cell for verification of total assembly mass. All of the ancillary data from each measurement position is logged to an ID- and time-specific data file. In addition, a summary log file of final measurement results is produced to enable the operator to document and report results from any time frame so chosen. Figure 6 shows this window, which allows the operator to select what type of measurement report to generate over any chosen time interval.

Once the ID of the current assembly is entered, the actual measurement procedure begins. The software directs the operator to place the assembly at different axial locations within the SFCC. These measurement locations are predetermined based upon the type of analysis and the assembly to be measured. A very general measurement technique used for abnormal, damaged, or a disassembled spent fuel assembly is to integrate over the entire axial length of an assembly.

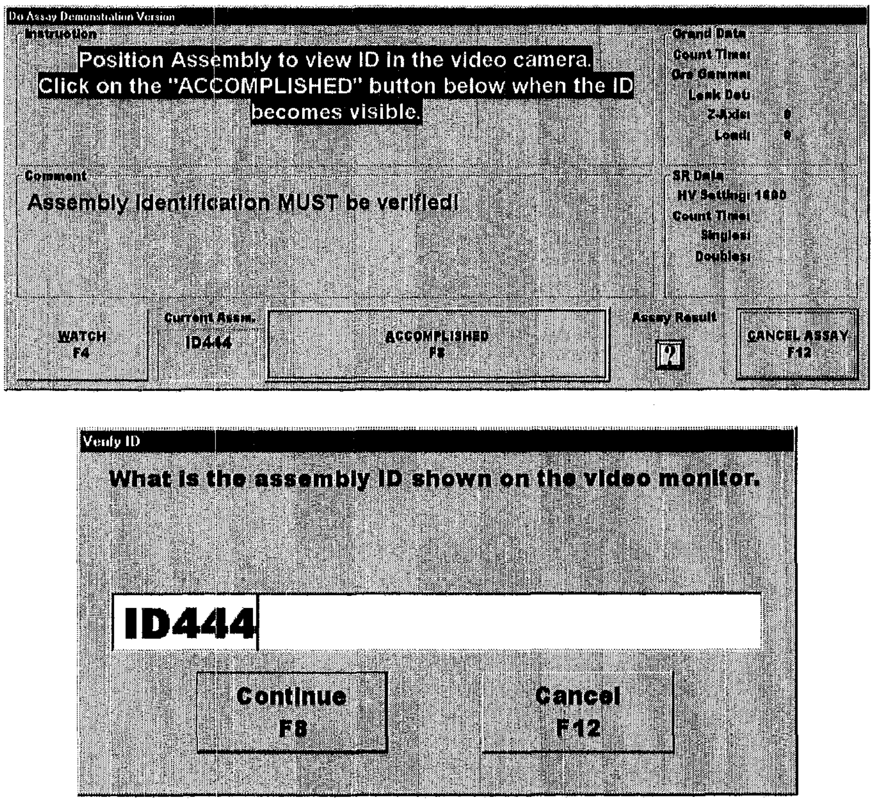

Fig. 5. The ID prompt and ID data entry windows that would be sequentially visible to the measurement technician or inspector.

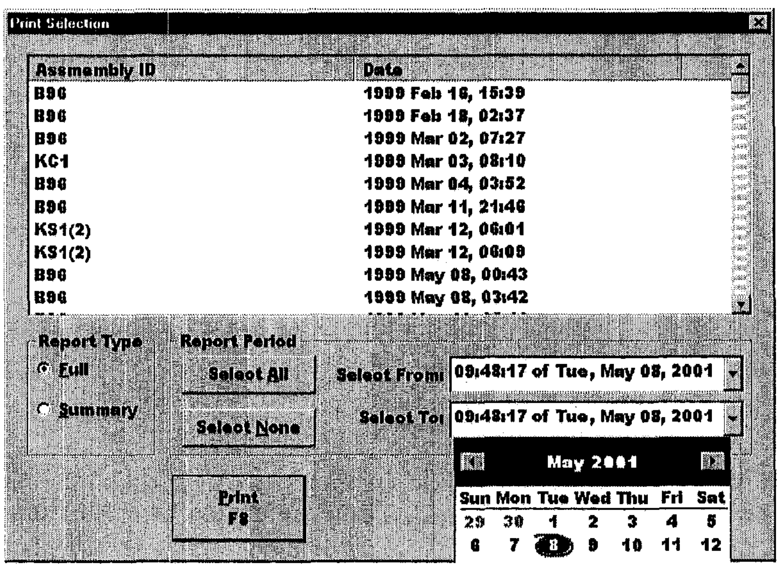

Fig. 6. The "generate report" program window that allows the operator to select a predetermined measurement report type to generate over any chosen time interval to enable rapid documentation of results.

The integration is performed using the measured plutonium density obtained from 25-cm-interval SFCC measurements. It requires approximately 15 minutes to perform both positioning and data collection from a 2-meter long active area of a spent fuel assembly. Figure 7 shows the program window that prompts the operator to begin such measurements.

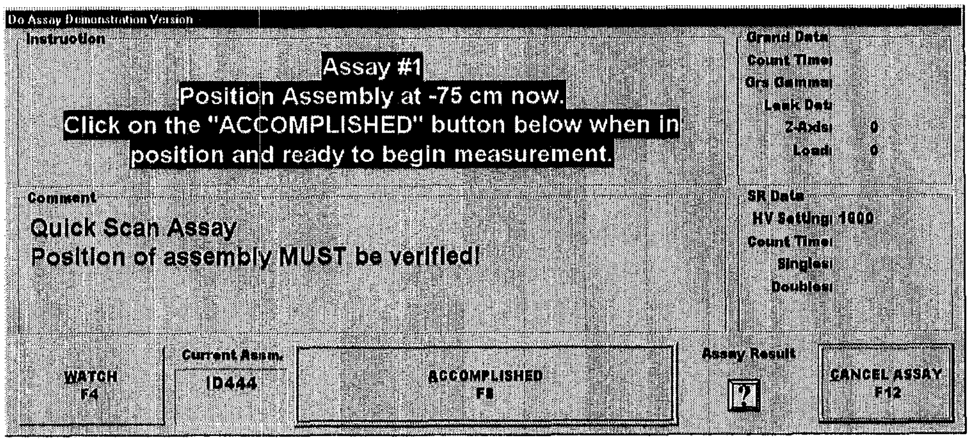

Fig. 7. The begin measurements program window that prompts the operator to proceed with the assay.

The final measurement analysis results are immediately shown at the conclusion of the measurement series along with Pass/Fail information. The Pass/Fail criterion is according to IAEA measurement requirements for the Partial Defect Test, one of the tests applied in this case. Figure 8 shows the final analysis results window along with a summary of the measurement results and some user specific data entry boxes to record initial and final storage locations. The basic software package can be readily customized to facility specific user requirements relating to operations, procedures and analysis required.

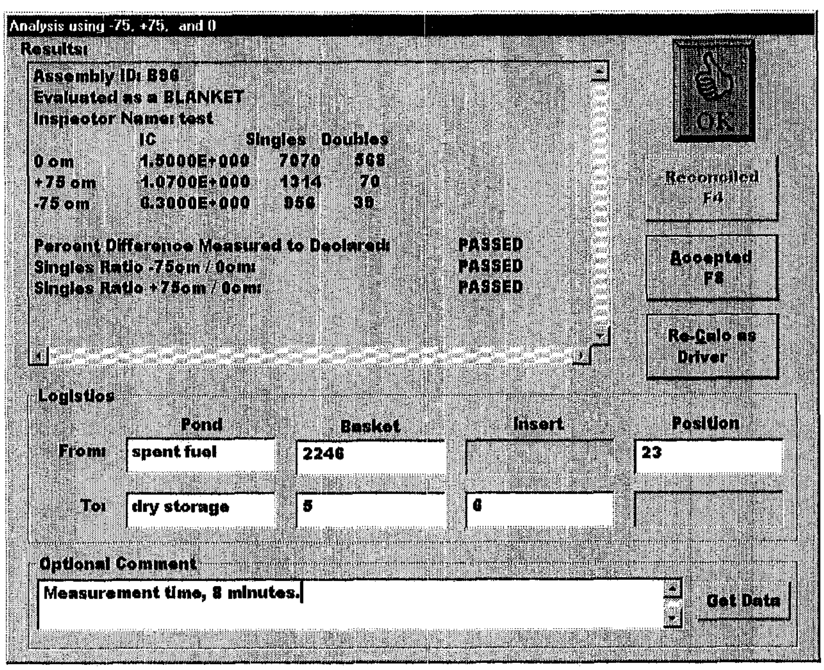

Fig. 8. The final analysis results window along with a summary of the measurement results and some user specific data entry boxes to record initial and final storage locations.

OTHER PROJECTS

With the completion of the Packaging Campaign at the BN350, the US/DOE and the IAEA are now finalizing installation of a larger SFCC (called SPAM, SPent fuel Attribute Monitor) that will enable verification measurements of the repackaged material. The software interface is similar to the SFCC software, with the most significant exception being the window shown in Fig. 9, the main operational screen to determine if measurement control, baseline, or actual reverification measurements are to be performed. The baseline option is not available when the software is configured for reverification work and vice-versa.

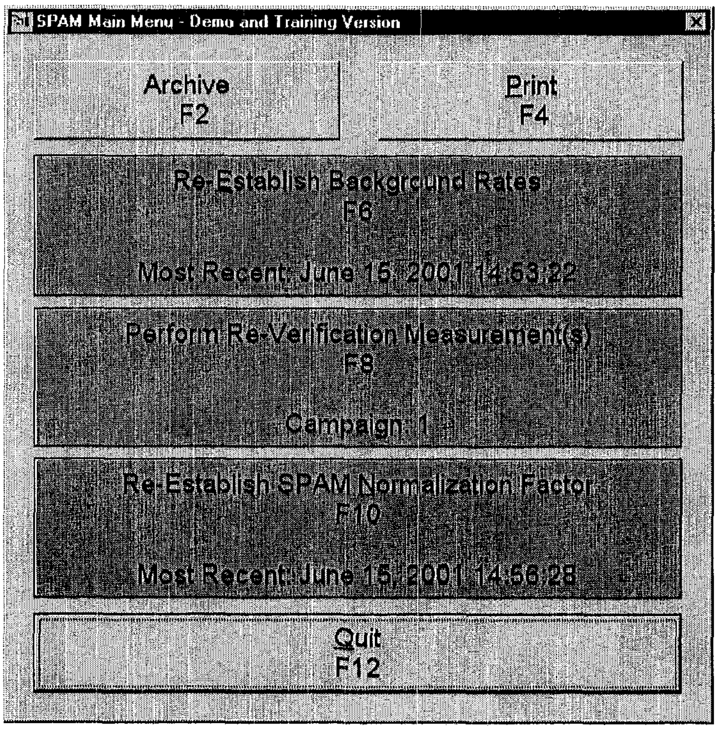

Fig. 9. SPAM measurements option window for the reverification measurements of BN350 repackaged spent nuclear fuel.

We are also undertaking a program to update the software and data analysis interface used with Fork Detectors, simple gross neutron/gross gamma spent fuel characterization instruments used by the IAEA for power reactor spent fuel measurements. Status and the plans of this new project will be presented in the Oral accompaniment to the paper.[5]

CONCLUSION

NDA measurement approaches can be limited when attempting to measure spent fuel, usually by very high radiation levels or by the presence of other various by-products of reactor operations (typically the presence of Curium isotopes). Our current SFCC and SPAM detector designs have been or are designed to be operated in radiation fields as high as 150,000 R/hr, at contact, and we understand the design requirements to enable operation in radiation fields an additional order of magnitude higher. As such, we no longer are hindered in the routine measurement of spent fuel by the radiation fields that are associated with such material. With respect to the presence of Curium isotopes within the spent fuel, there are a few notable exceptions, with the most significant being spent fuel in the following categories: breeder reactor fuel, low-burnup or long-cooling-time fuel. When Curium is present in significant quantities in the spent nuclear fuel we can readily determine the burnup of the spent fuel, but fissile content determination is difficult and presents associated large uncertainties. For the IAEA, SFCC measurements in the Republic of Kazakhstan, we have quantified the Plutonium content of the spent fuel using minimal facility input regarding knowledge of the fuel geometry or initial isotopics. The limited prior knowledge analysis algorithms used with the IAEA's instrument have provided a bias of less than 0.2% with respect to the operator's declared mass and an RMS difference of approximately 13% for well over 2000 spent fuel assemblies measured. With the use of more detailed spent fuel assembly knowledge, our RMS error drops to approximately 8%, keeping in mind that this value also includes the error in the facility operator's declaration, not just the measurement error. Every facility has at least a limited understanding of the material in its repositories. The major and obvious drawback of having less information available to the measurement specialist is that the less knowledge available, the correspondingly larger are measurement errors associated with any type of assay. The typical measurement time per assembly in the Republic of Kazakhstan with the SFCC is less than 15 minutes. The measurement and analysis software is very simple to use, and IAEA inspectors, many of who are not even specialists in the field of nuclear physics, perform the entire process. The standardization of the software to perform spent fuel measurements should greatly improve IAEA inspector success and productivity. This will free the inspector to perform other duties associated with inspections. In addition, the modernization of the software will ensure compliance with standard computer operating systems in use throughout the world.

ACKNOWLEDGMENTS
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